Stable, High Tuning Range, Micromachined Varactors for Space Applications

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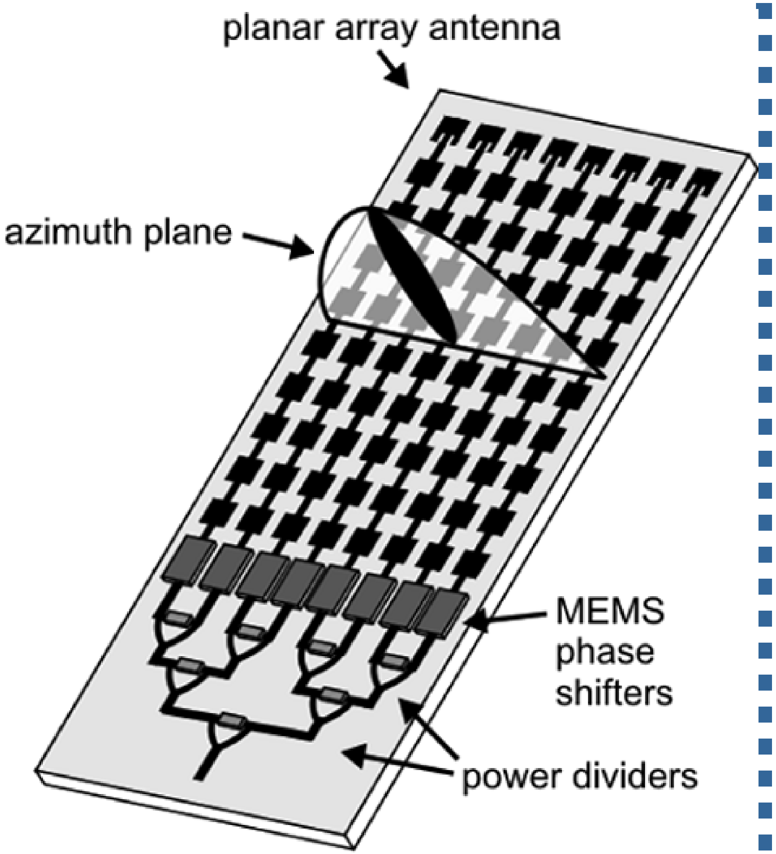
Outline

- **Introduction: Space and RF MEMS Technology**
- Varactor Concept
- Fabrication
- Measured & Simulated Performance
- Surface Roughness in MEMS Varactors
- Related Work: Modelling & Packaging
- Conclusion

Reconfigurable circuits for space applications

- Electronically steerable antennas (ESA) use tunable electronic components to alter the phase of individual radiating elements, and so enable the radiated beam to steer without any mechanical motion of the antenna system.
- ESAs have applicability in satellite communications systems, e.g. a single ESA could enable simultaneous tracking and communicating of multiple objects.
- Beam steering is currently achieved using phase shifters, which typically employ GaAs varactors – these are expensive and lossy.
- Microelectromechanical switches and varactors could reduce losses and costs.



- Adapted from Schoebel, *IEEE Microwave Theory and Techniques* **53** (6), 2005

RF MEMS

- Small, lightweight, adaptable - may be batch fabricated on a variety of substrates.
- Low mass – suitable for space applications.
- Excellent RF Characteristics:
  - Superior RF performance in comparison with market leading PIN diode and GaAs MESFET technologies
  - Lower insertion loss, higher isolation (switches)
  - Higher tuning range and quality factor (capacitors)
- Primary applications of capacitive switches/varactors will lie in the implementation of tunable, low-loss circuits for telecommunications:
  - Phase shifters, antenna steering, radar impedance tuning for multiband radio, antenna tuning, transceiver integration….
- This presentation outlines the design and development of a MEMS-based varactor for use in reconfigurable telecommunications.

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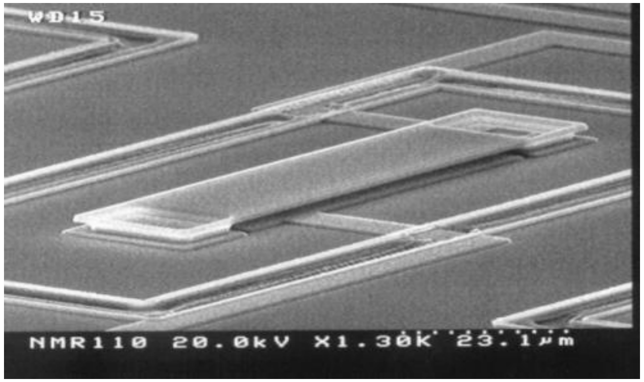
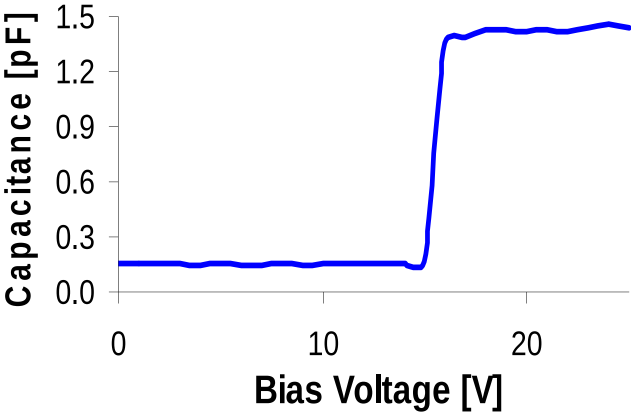
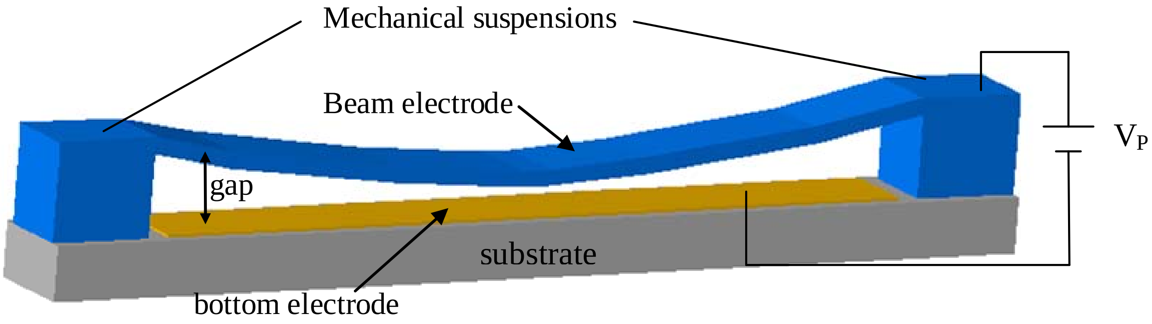
Micromechanical Varactors

- MEMS varactors use mechanical forces to move one plate relative to another and thereby tune the capacitance of the device.
- Basic MEMS varactors are parallel-plate devices.
- Tuning limited to 50% by the electrostatic pull-in effect – unsatisfactory
- Major efforts underway to extend this range.



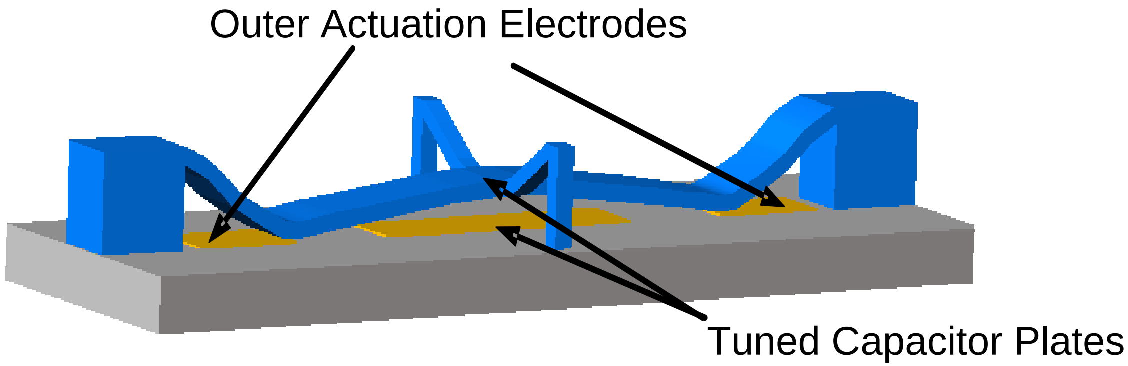


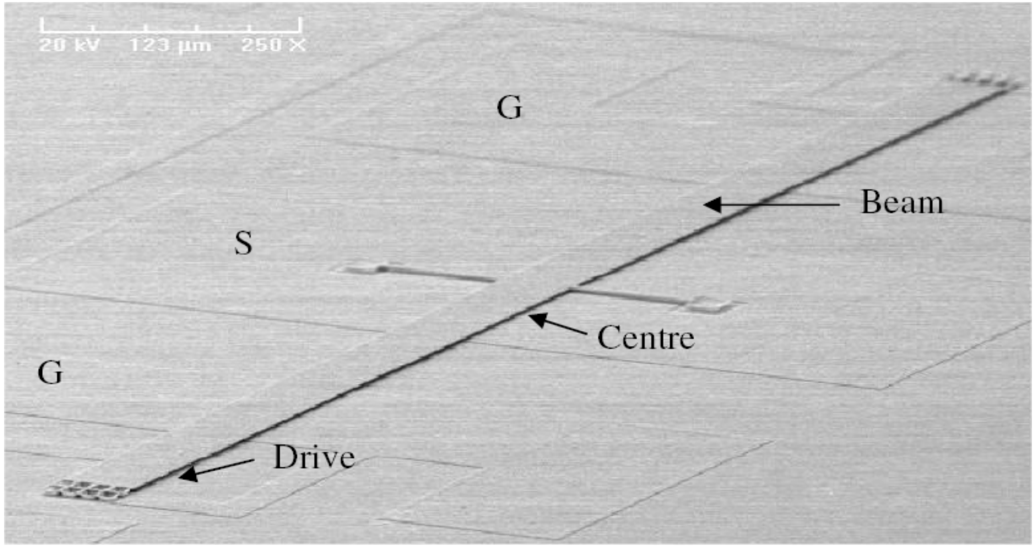


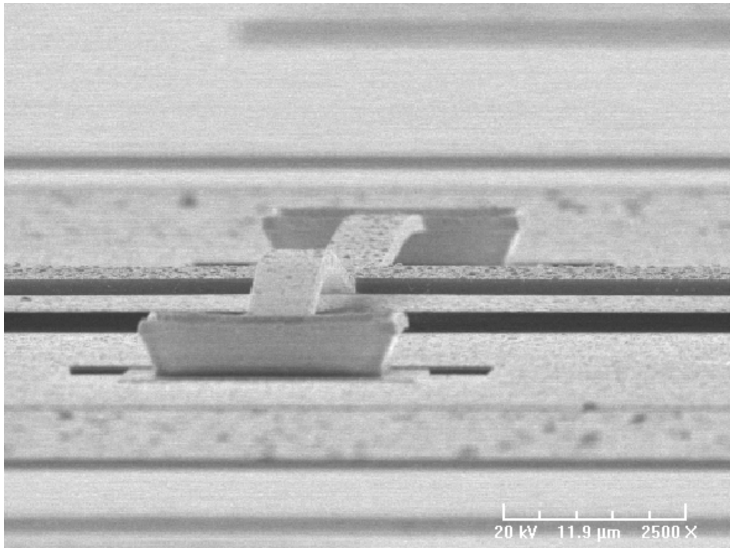
$$C = \varepsilon A / d$$

New design: 'Hill-Shaped Zip-up' Capacitor (HZC)

- Novel design has potential to achieve very high tuning range
- Based on leveraged bending using a multielectrode structure







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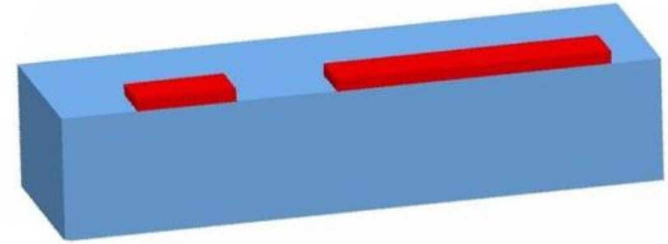
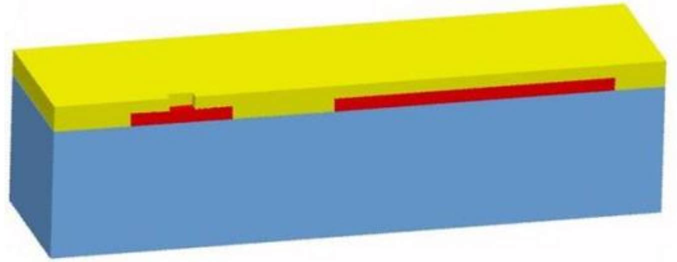
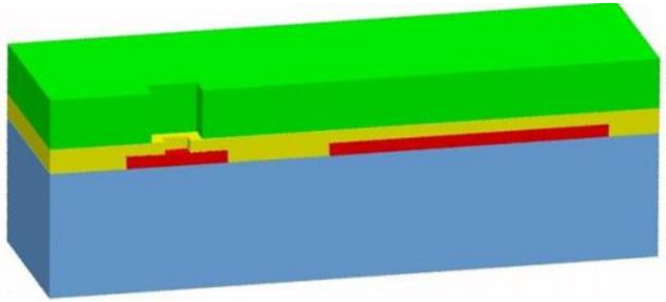
Varactor Fabricaton



- Substrate and metal level (Metal2- $0.5\mu m$ Al/1%Si)
- Pattern Metal2 for
  - circuit to device contact
  - MEMS electrodes

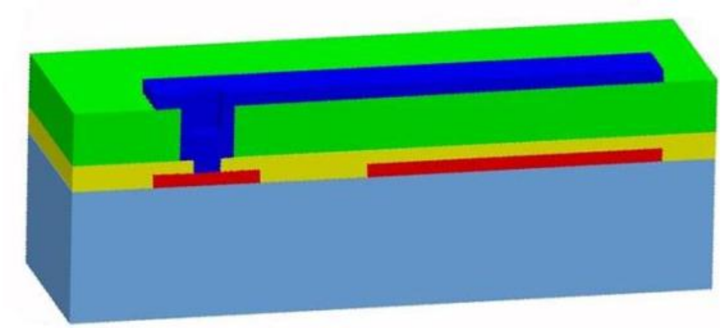


- PECVD dielectric ($0.1\mu m$ SiO_2) to prevent MEMS short circuit

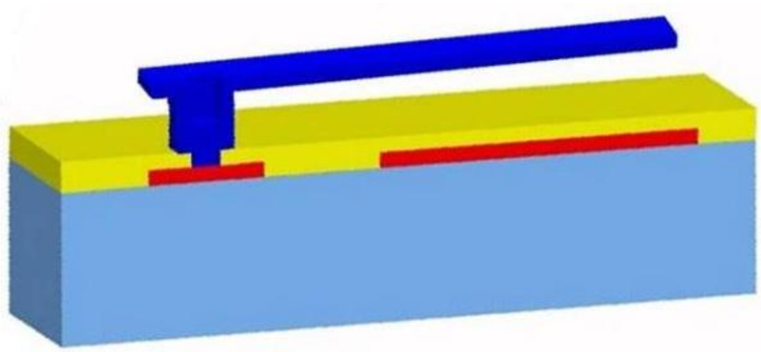


- Spin and cure sacrificial layer ($2.5\mu m$ polyimide) and open beam anchor holes

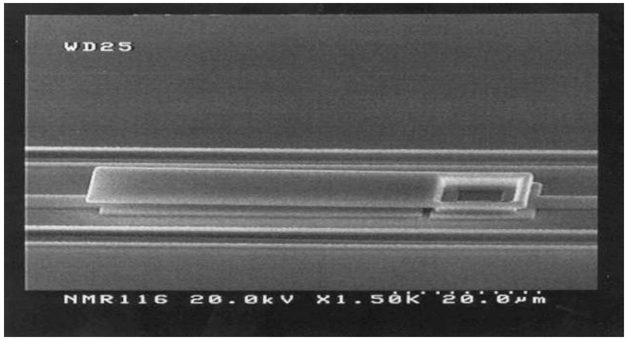
Varactor Fabricaton



- Cold sputter structural layer (1.0μm Al)



- Dry-release with polyimide etch in an oxygen plasma



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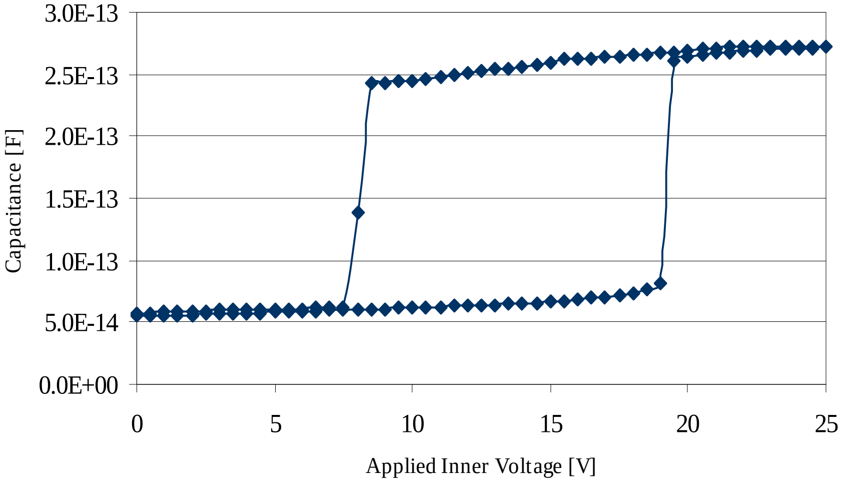
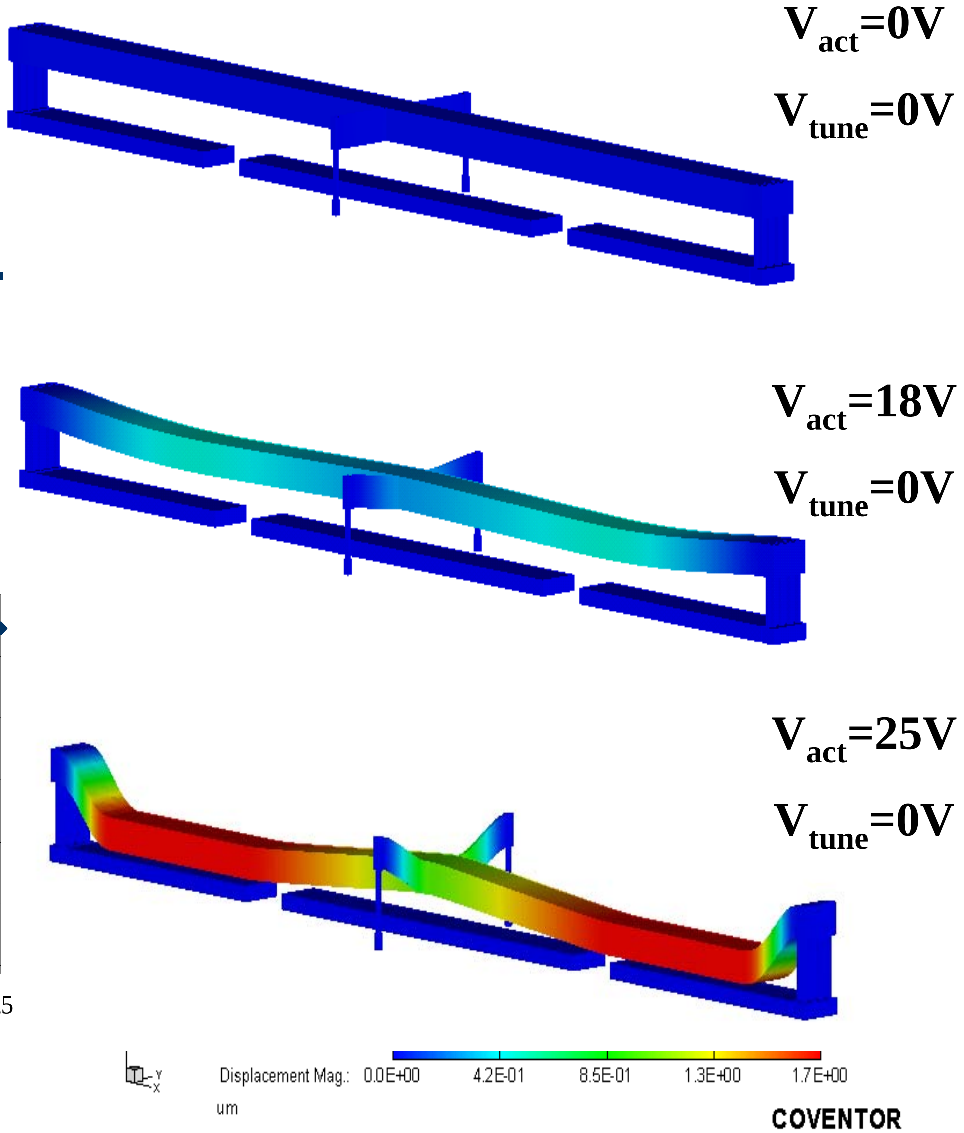
Phase 1: Actuation

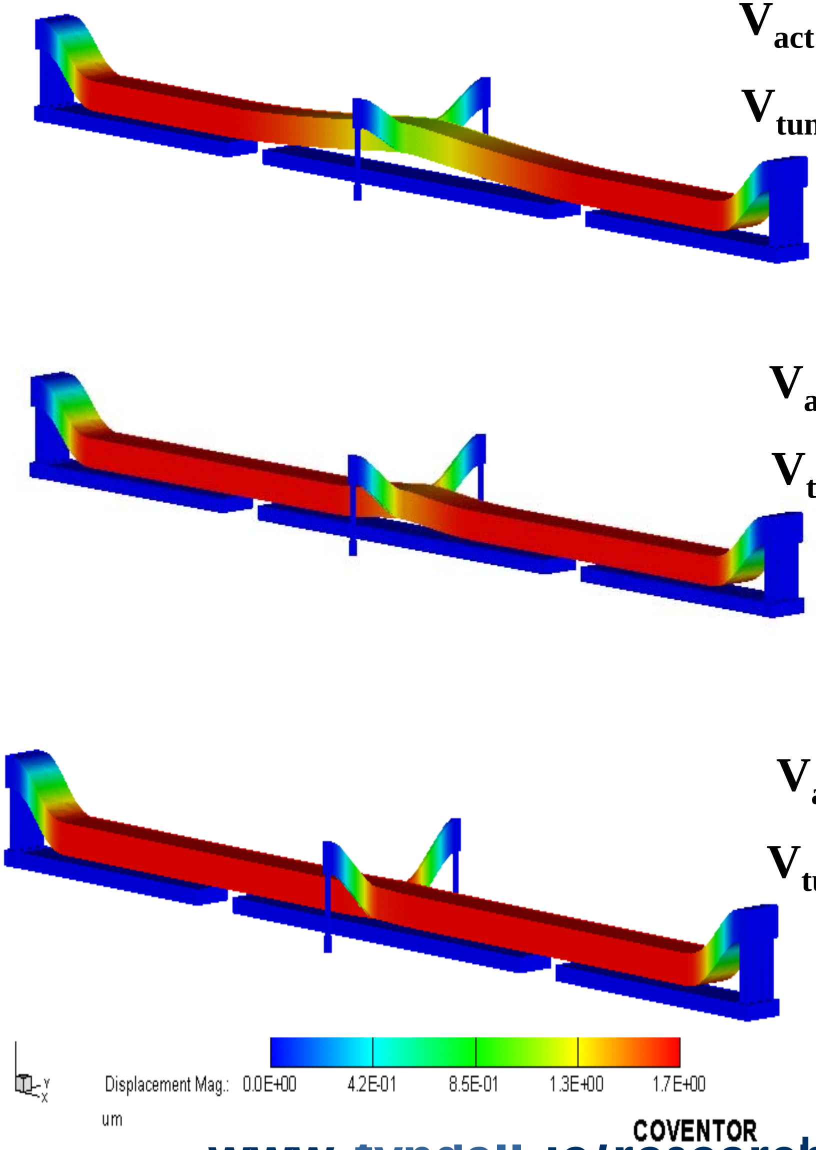
- Actuation voltage applied to outer electrodes.
- Central beam bending is restrained by lateral tethers.
- A combination of these opposing forces bends the capacitive electrode into a ‘hill-shape’.





Phase 2: Tuning

- Voltage applied to inner capacitive electrodes to tune the device capacitance.
- Beam ‘zips-up’ along the central electrode
- No instability point since a parallel-plate structure no longer exists >> continuous tuning.



V_{act}=25V

V_{tune}=4V

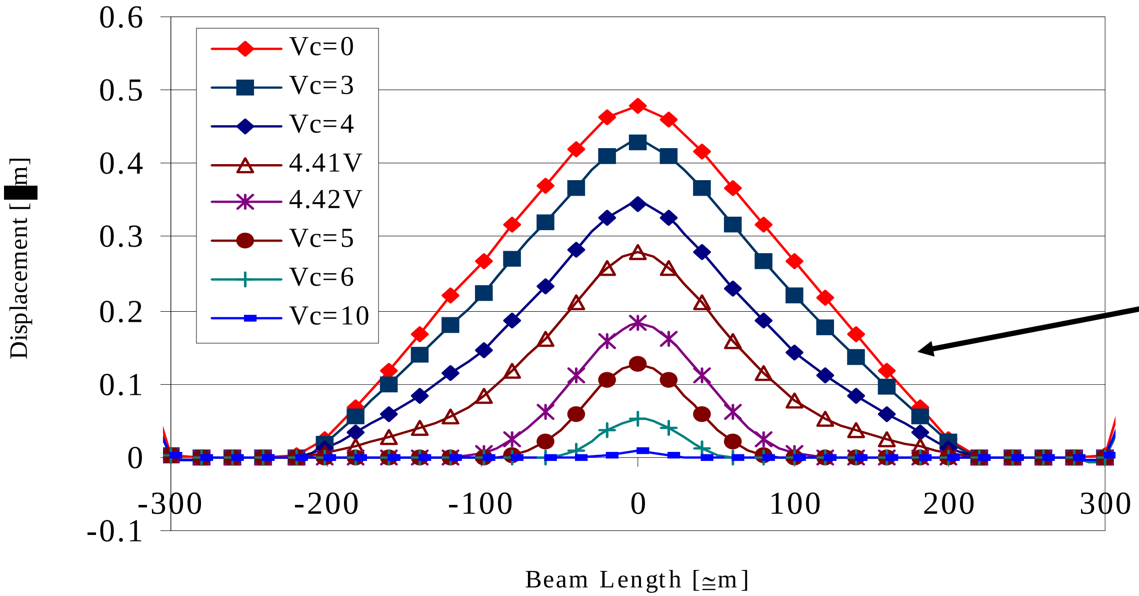
V_{act}=25V

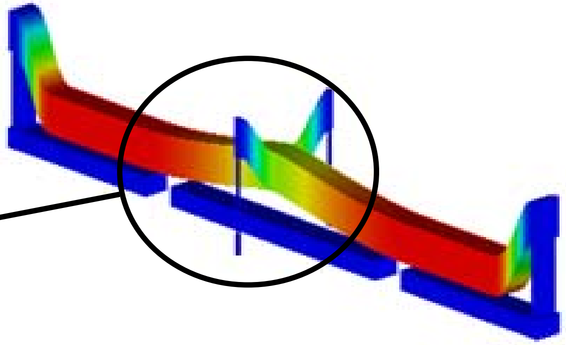
V_{tune}=6V

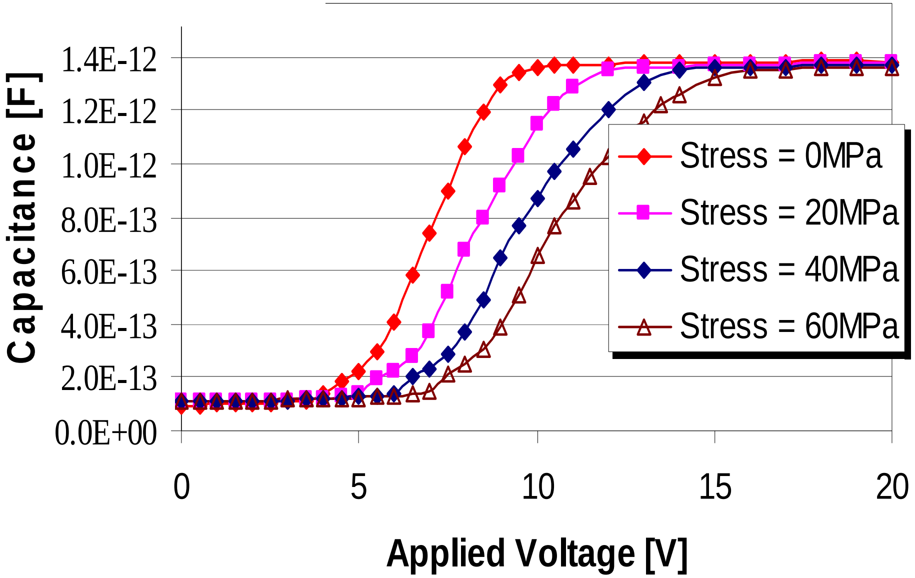
V_{act}=25V

V_{tune}=10V

Simulated Performance



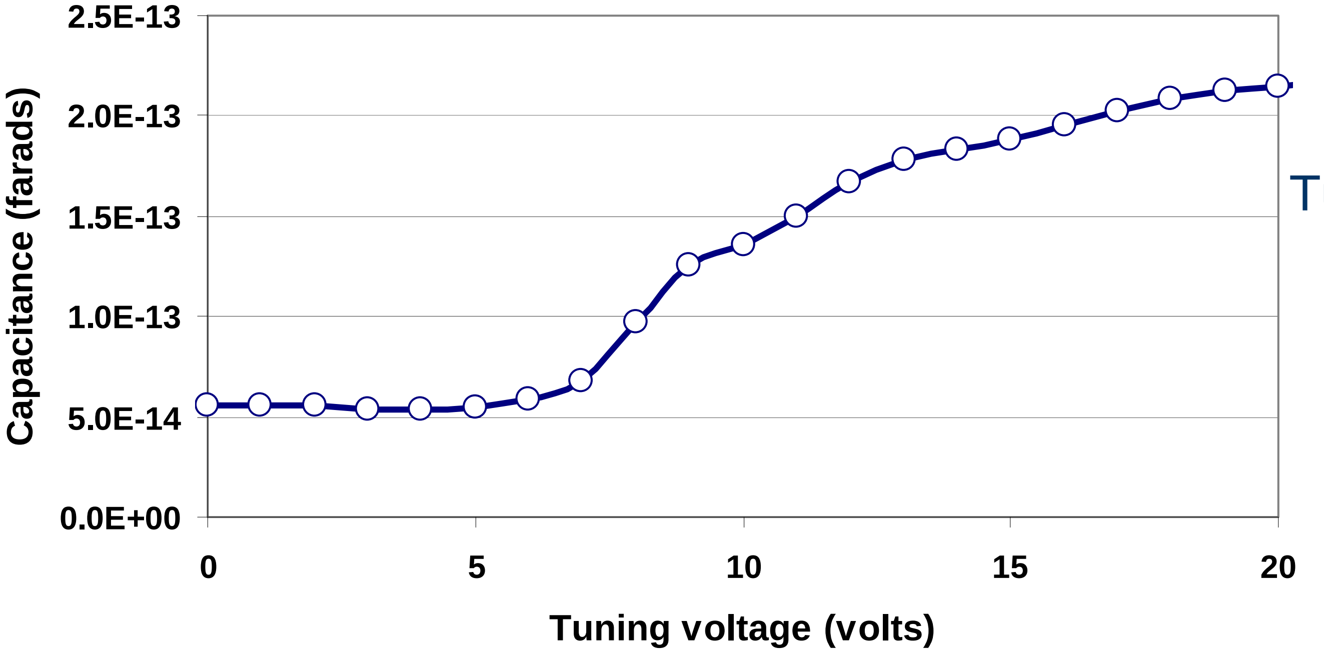




- Potential tuning Range >500%
- Tuning voltage goal <20V

Measured Performance

- First measurements show tuning ranges of up to ~150% at 10V, 286% at 20V.
- C-V curve shape agrees well with simulations; no instability point.
- Tuning Range much less than expected due to –
  - (a) lower-than-expected initial gap height;
  - (b) surface roughness of the bottom electrode.



Tuning Range:
- 144% @ 10V
- 286% @20V

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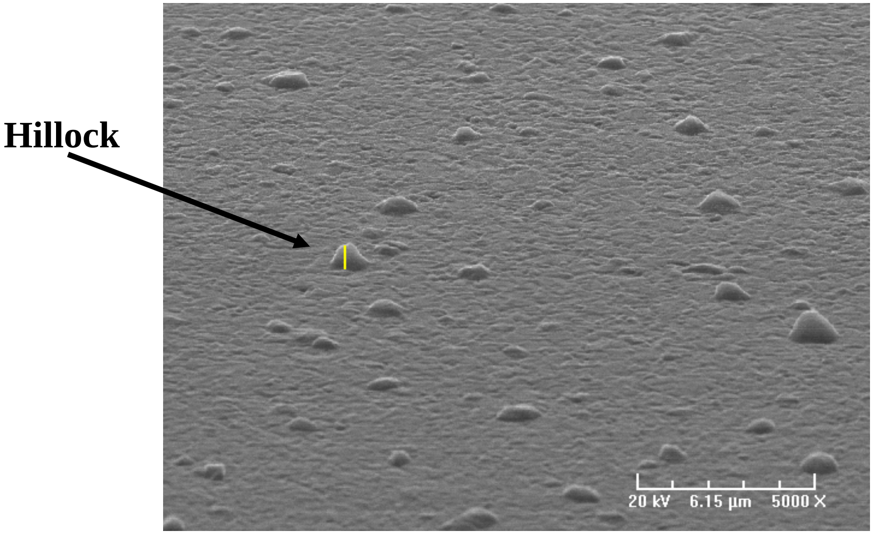
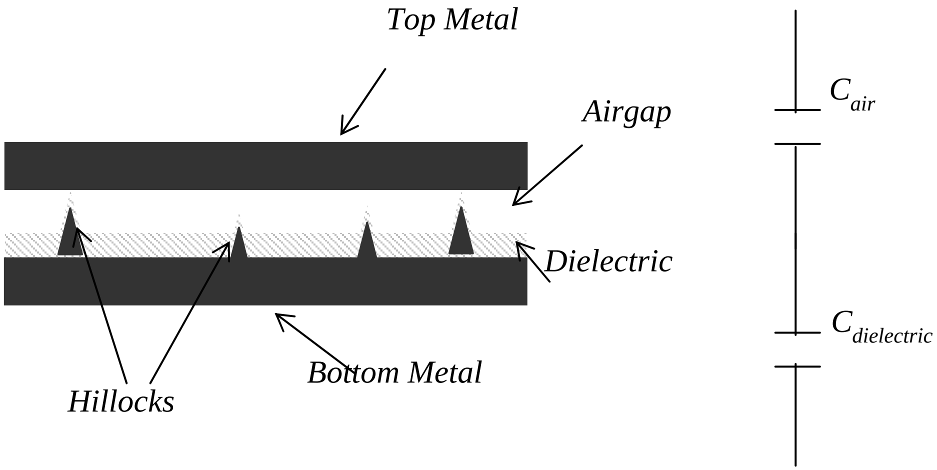
Surface Roughness

- High capacitance tuning requires perfect contact between the beam and the substrate metal electrode; thermal ‘hillocking’ of the metal prevents this.

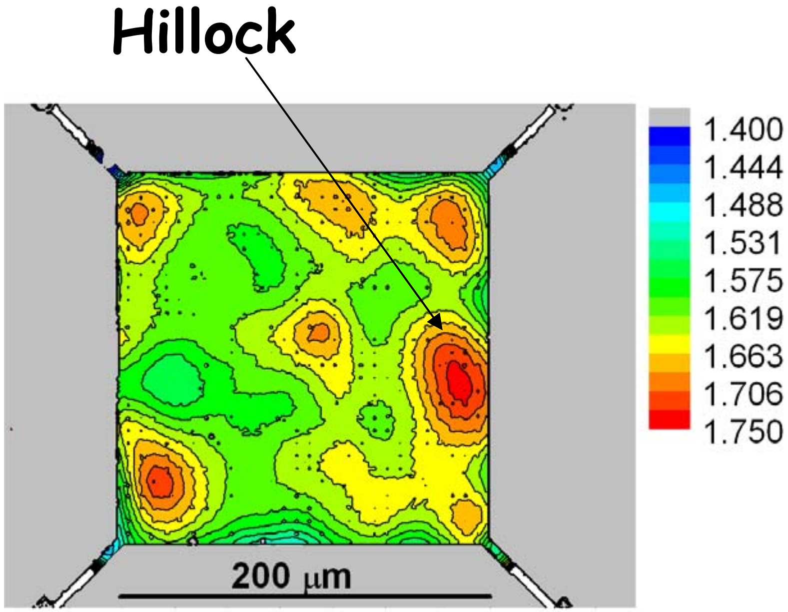




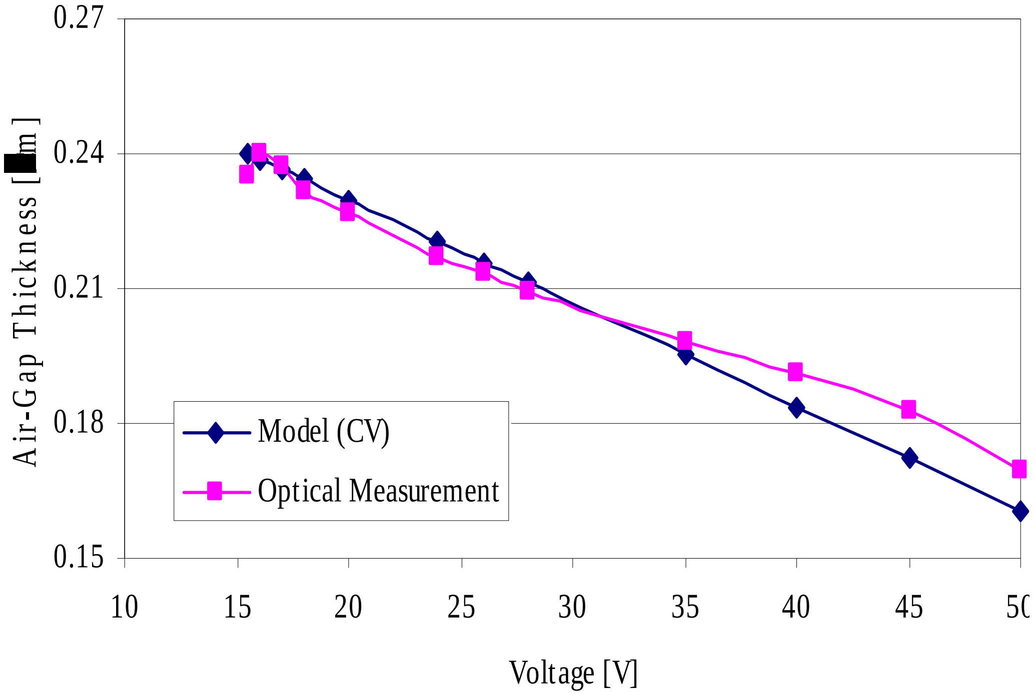
- Contact capacitance is now a series connection of air-gap and dielectric capacitances
- In practice, some roughness is unavoidable; excessive roughness causes poor performance in RF varactors and switches

Surface Roughness

- Roughness analysed using membrane-type switches and both optical and electromechanical tests
- ‘Residual gap’ due to roughness is voltage-dependent but is of the order of 0.1-0.3μm
- Voltage-dependent airgap model: $t_a(V) = t_{a_0}(1 - t_s * (V - V_{pi}))$
- Model parameters: t_{a0} = 0.2μm; t_s=2.5nm/V

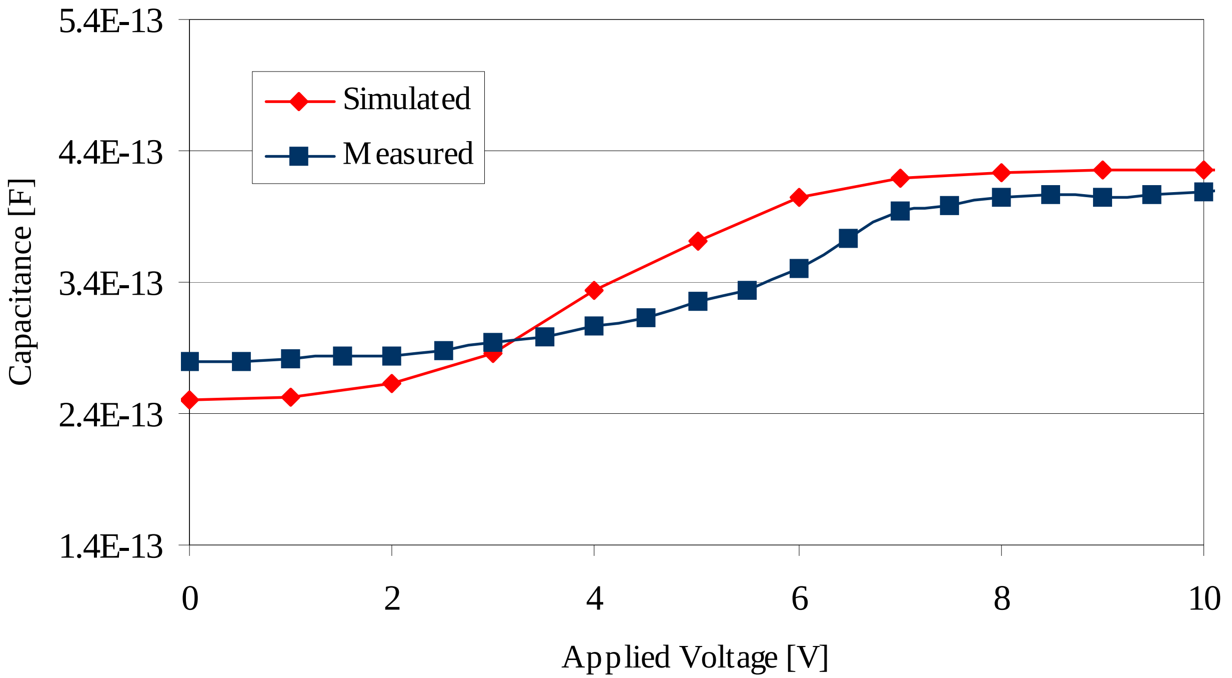


V = 15.5V



Surface Roughness

- Roughness is the source of (relatively) low capacitance ratio.



- Will never achieve full tuning (in practice, nanoscale roughness will always reduce capacitive switch/varactor range by ~50%).
- Working on reduction of roughness using (*i*) low-temperature processing and (*ii*) physical barrier capping.

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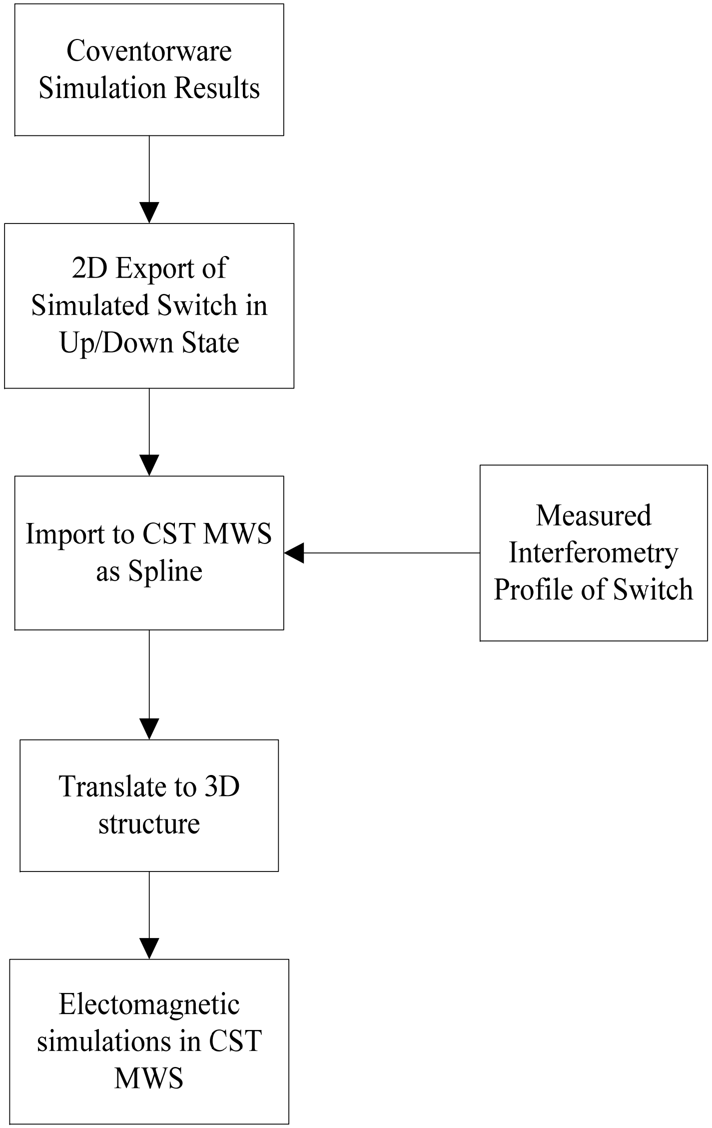
Integrated Modelling

Adaptive Wireless Systems


Coventorware Simulation Results

2D Export of Simulated Switch in Up/Down State

Import to CST MWS as Spline

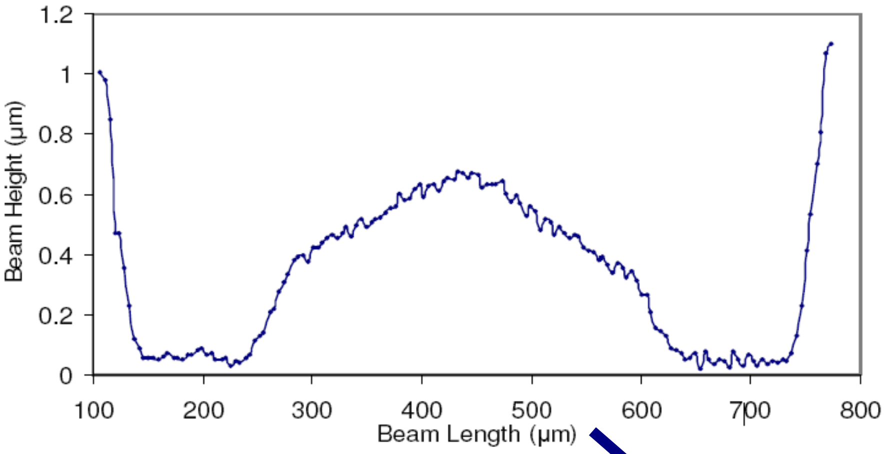
Measured Interferometry Profile of Switch

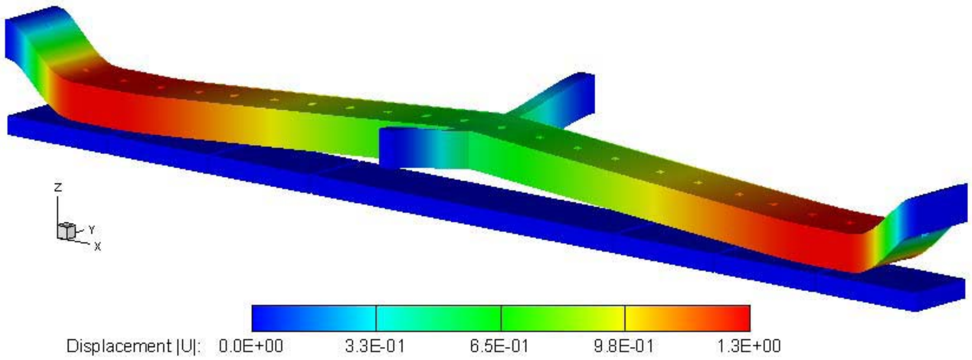
Translate to 3D structure

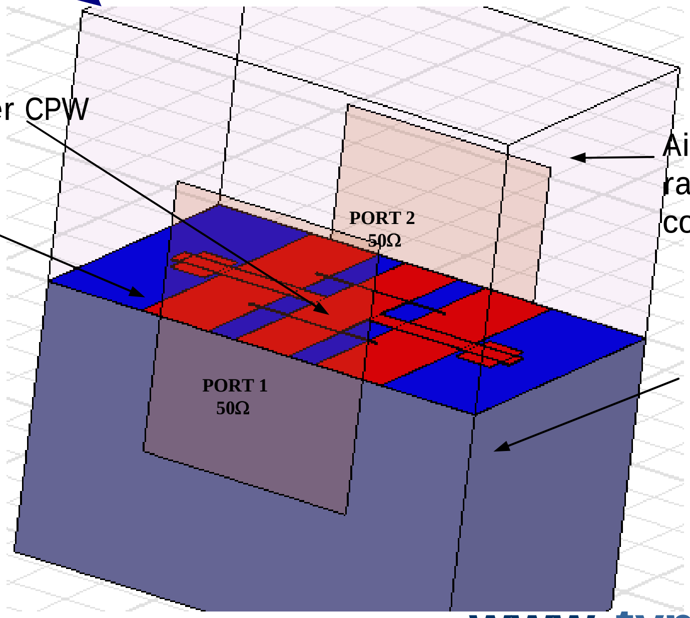
Electomagnetic simulations in CST MWS

- MEMS devices are often (poorly) approximated as ideal or ‘parallel-plate’ structures.
- ‘Integrated modeling’ allows the use of both real and simulated MEMS geometries and shapes to analyse RF performance.
- Coventor for electromechanical modelling; interferometry for measured deflection profiles.
- The measured and simulated surface profiles are imported into CST Microwave Studio and extruded to the switch dimensions.
- The switch is translated into a 3D structure for electromagnetic simulations.

Integrated Modelling







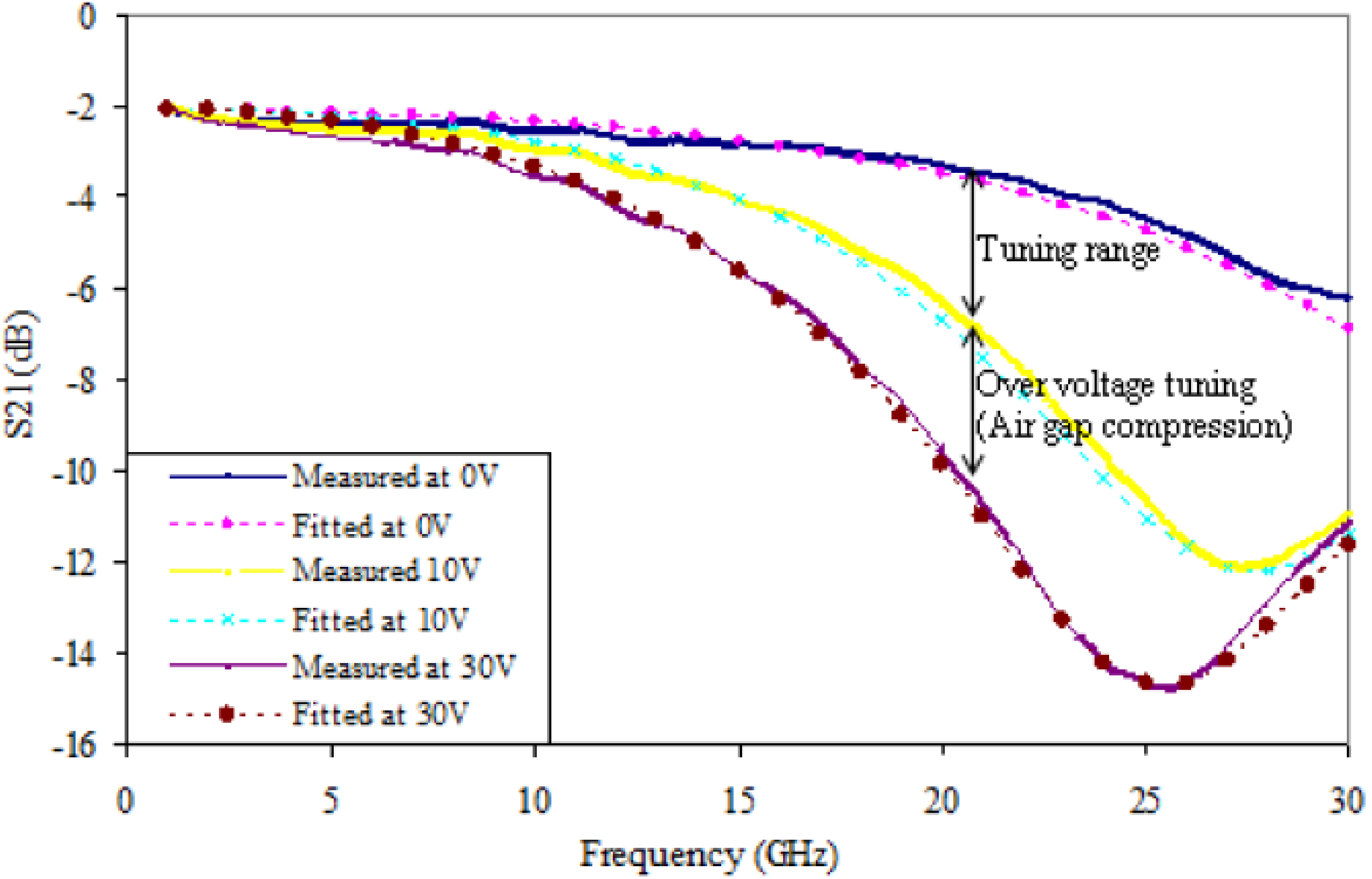
Varactor over CPW

0.5µm thick SiO_x
on silicon substrate

Air box with imposed
radiation boundary
conditions

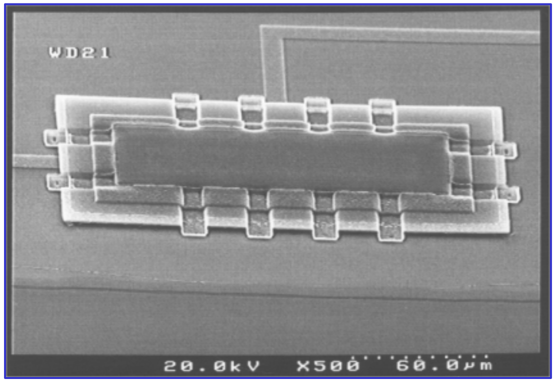
Silicon substrate

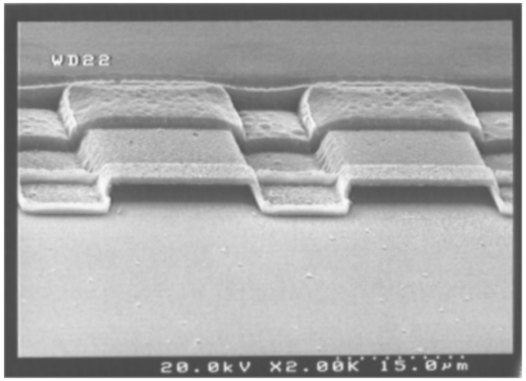
Example – S_{21} Simulation

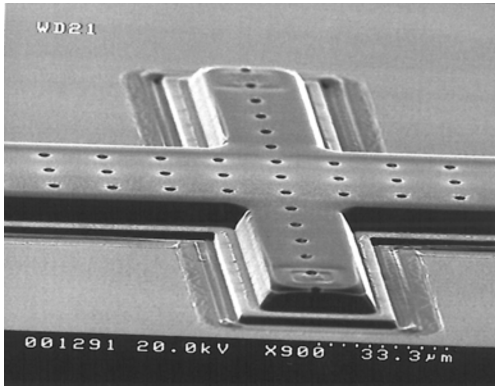


Thin-Film Packaging

- MEMS packaging essential for high reliability.
- Packaging can account for >75% of total cost of the device and is often bulky.
- This work is also investigating ‘wafer level’ thin film packaging with oxide and metal lids.
- Low-temperature assembly- allows use of materials such as polyimide and aluminium.
- Process for sealing etch holes or channels still being tested.







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Summary

- Novel varactor design has the potential to achieve a very high tuning range.
- Planar fabrication but no parallel-plate operation; no pull-in instability in characteristic C-V tuning curve (continuous tuning).
- Current maximum tuning ratio is 286% at 20V.
- This ratio will be improved by reducing surface roughness – current work.
- Low sensitivity to residual fabrication stress and temperature.
- Inherently switched capacitance through actuation to initial profile.
- Requires no additional MEMS processing steps.
- May be integrated with wafer-level packaging technology.

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